O'Mega & WHIZARD:
Monte Carlo Event Generator Generation
For Future Colliders

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Contents

Future Colliders as New Frontier in Energy and Precision:

- final states with many tagged weakly interacting particles accessible

- *(in the absence of low energy SUSY:)* physics beyond the standard model may only be accessible in precision tests of standard model processes

∴ we will need reliable predictions and simulation tools to unleash the full potential of the Future Colliders

- – studying EWSB requires complete (gauge invariant!) calculations
- – polarization must be included

qualitatively more complicated than, say, LEP1

- – the number of Feynman diagrams explodes combinatorially
- – the algebraic expressions grow much more complicated with the growing number of building blocks (independent momenta and polarizations)
- – the gauge cancellations become extremely hazardous
- – the phase space also becomes much more intricate

∵ even if we had enough graduate students and postdocs, we should not waste them on repetitive "assembly line" calculations

∴ formalize the calculations so that the repetitive part can be delegated to patient computers. Ideally:

$$\left.\begin{array}{c} \text{Lagrangian, parameters} \\ \text{final state, cuts} \end{array}\right\} \implies \text{efficient unweighted event generator}$$

☺ partial solutions exist (CompHEP, Grace, and MADGRAPH), progress in Y2K

- fast and complete tree level calculations for arbitrary models:
  O'Mega (T. O. et al.)

- adaptive phase space generation for many particles:
  WHIZARD (Wolfgang Kilian), [using VAMP (T. O.)]

☹ some essential parts will need a lot more work

- loops for many particles

∵ one-loop calculations for $2 \to 4$ remain the limit of our capabilities

The number of tree Feynman diagrams w/ n legs in vanilla ϕ^3-theory is

$$F(n) = (2n-5)!! = (2n-5) \cdot (2n-7) \cdot \ldots \cdot 3 \cdot 1$$

n	$F(n)$	$P(n)$
4	3	3
5	15	10
6	105	25
7	945	56
8	10395	119
9	135135	246
10	2027025	501
11	34459425	1012
12	654729075	2035

☹ computational costs grow beyond all reasonable limits

☹ gauge theory cancellations cause loss of precision

Number of independent momenta

$$P(n) = \frac{2^n - 2}{2} - n = 2^{n-1} - n - 1$$

∴ Feynman diagrams extremely redundant for many particles in the final state!

☹ terms much too large to expect any help from common subexpression elimination by optimizing compilers that don't understand any physics!

Directed Acyclical Graphs (DAGs) are a more efficient representation for arithmetical expressions than the equivalent trees. E. g.:

$$ab(ab + c) =$$ $$=$$

One particle off-shell wave functions (1POWs):

$$W(x; p_1, \ldots, p_n; q_1, \ldots, q_m) = \langle \phi(q_1), \ldots, \phi(q_m); \mathsf{out} | \Phi(x) | \phi(p_1), \ldots, \phi(p_n); \mathsf{in} \rangle \ .$$

E. g. $\langle \phi(q_1), \phi(q_2); \mathsf{out} | \Phi(x) | \phi(p_1); \mathsf{in} \rangle$ in unflavored scalar ϕ^3-theory at tree level

- the set of tree level 1POWs forms a DAG and can be constructed recursively

- Theorem: all tree level scattering amplitudes can be represented by combinations of 1POWs (correct combinations are termed keystones)

- this DAG can be constructed algorithmically and contains no more redundancies

Matrix element compiler O'Mega:

- functors building applications from independent modules for

  – physics models `Models.SM, Models.SM_ac, Models.MSSM,...`

  – target languages `Targets.Fortran,...`

- E. g. the application writing Fortran95 for the standard model is

```
module O = Omega.Make(Fusion.Mixed23)
                  (Targets.Fortran)(Models.SM)
let _ = O.main ()
```

- any volunteers for Java and `C++` targets?

- O'Mega Virtual Machine on a chip???

- O'Mega amplitudes for up to 7 particles ("$2 \to 5$") tested against MADGRAPH

  🙂 agreement for random momenta always better than 10^{-11}

- Get it from `http://www.ikp.physik.tu-darmstadt.de/˜ohl/omega/`.

First realistic application

- Roberto Chierici, Stefano Rosati, Michael Kobel: full simulation of six fermion final states in W^+W^- scattering for the TESLA Technical Design Report, using WHIZARD by Wolfgang Kilian as unweighted event generator.
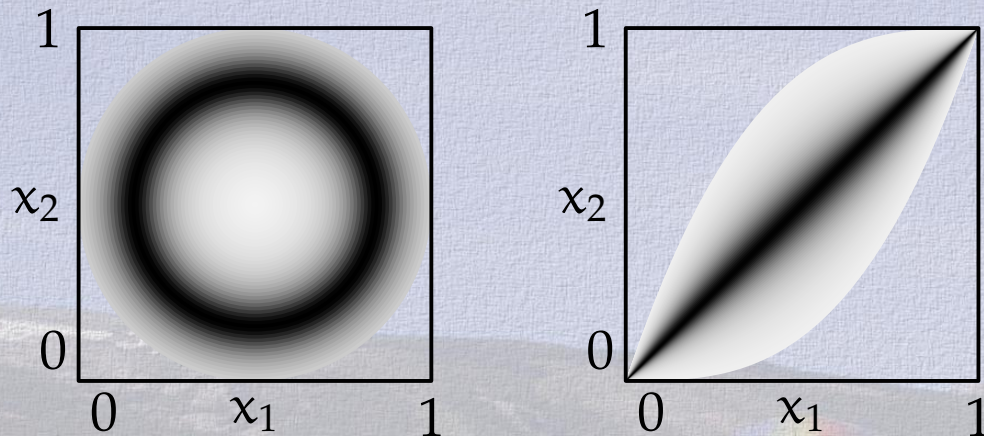
New Frontiers:

- QCD and color amplitudes still incomplete, but solution known, only coding required

- Supersymmetry and general MSSM exist in a preliminary versions, automated consistency checks under construction

- weak scale Gravity under construction

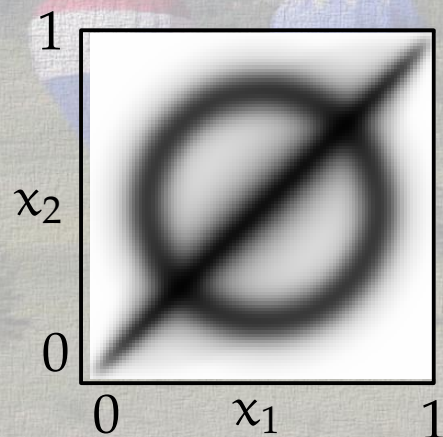- O'Giga: O'Mega Graphical Interface for Generation and Analysis

VEGAS' factorized ansatz can deal with

separately after appropriate mapping.

🙁 fails for overlapping singularities

which is the common case (if more than one diagram contributes)

∴ adaptive multichannel approach

$$I(f) = \int_{M} d\mu(p)\, f(p)$$

$$I(f) = \sum_{i=1}^{N_c} \alpha_i \int_0^1 g_i(x) d^n x\, \frac{f(\phi_i(x))}{g(\phi_i(x))}$$

with

$$g = \sum_{i=1}^{N_c} \alpha_i \cdot (g_i \circ \phi_i^{-1}) \left| \frac{\partial \phi_i^{-1}}{\partial p} \right|$$

🙂 works with factorized g_i adapted by VEGAS and α_i adapted by variance reduction.

☺ in general, $g \circ \phi_i$ **does not factorize**, even if all g_i factorize.

- $\pi_{ij} = \phi_j^{-1} \circ \phi_i$: coordinate transformations among coordinate systems in which different singularities factorize.

☺ pure geometry: **economical studies** of dependence on **cuts** and **parameters**

∵ π_{ij} universal and are calculated automatically by WHIZARD

∴ VEGAS can optimize the g_i for each set of parameters and cuts

However:

∵ singularity structure determined by **Feynman diagrams**

☹ **naive application** brings the **combinatorial explosion** in through the back door!

∴ WHIZARD selects the important channels

- s-channel resonances
- $1/t$-poles for massless particles
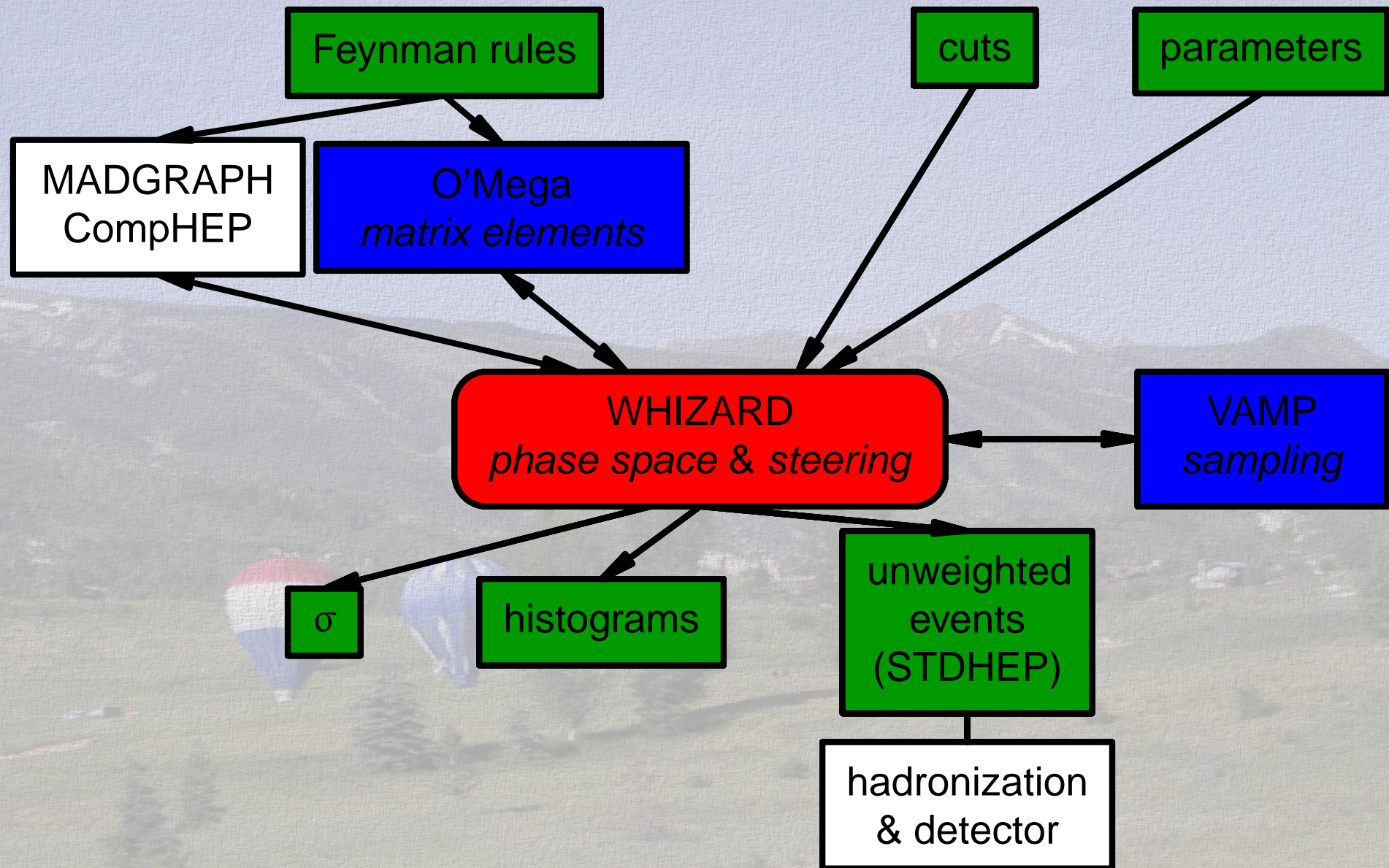
WHIZARD uses matrix elements from

O'Mega: polarized scattering of many weakly interacting particles, including unstable vector bosons and including (some) deviations from the standard model

MADGRAPH: polarized scattering of colored particles without gauge invariance problems from intermediate vector boson widths

CompHEP: faster for unpolarized scattering of few (possibly colored) particles

Usage:

Process file:

```
ID        In     Out            Method
zh        e1,E1  Z,H            chep
zww       e1,E1  Z,W+,W-        chep
nnbb      e1,E1  n1,N1,b,B      mad
nnucsd    e1,E1  n1,N1,u,C,s,D  omega
```

Compile: `Makefile` performs all necessary steps

- 21 diagrams in 4 groves (gauge invariant subsets): Higgsstrahlung (5), WW-fusion (10), ZZ (4), Z-FSR (2)

- Higgs signal topologies: `sss` and `stt`

- background topologies: `sss`, `sst`, `stt`, and `ttt`

Event generation at $\sqrt{s} = 350$ GeV for $m_H = 120$ GeV.

- In the first pair of steps, VAMP's VEGAS-grids are adapted with fixed relative weights of the channels

- WHIZARD summarizes VAMP's diagnostics

```
! It     Calls   Integral[fb]  Error[fb]  Err[%]  Err/Exp  Eff[%]   Chi2
!----------------------------------------------------------------------
! Adapting (fixed weights):   Generating 2 samples of 10000 events ...
   2     20000   5.7019717E+01  1.58E+00    2.76    3.91*    2.31     0.31
```

- ☺ efficiency not terrible …

- ☹ … `Err/Exp` too large

- In the following steps, the relative weights of the channels are allowed to vary

```
! It      Calls    Integral[fb]   Error[fb]   Err[%]  Err/Exp  Eff[%]    Chi2
!-------------------------------------------------------------------------------
! Adapting (var. weights):  Generating 8 samples of 10000 events ...
    3      10000    5.5642224E+01   1.23E+00    2.21    2.21*    7.58
    4      10000    5.9028368E+01   1.06E+00    1.80    1.80*    7.51
    5      10000    5.8586436E+01   8.34E-01    1.42    1.42*    9.82
    6      10000    5.8997829E+01   6.89E-01    1.17    1.17*   12.18
    7      10000    5.8626448E+01   1.04E+00    1.78    1.78    10.78
    8      10000    5.7737567E+01   5.12E-01    0.89    0.89*   17.50
    9      10000    5.7693393E+01   4.75E-01    0.82    0.82*   19.50
   10      10000    5.8216141E+01   5.42E-01    0.93    0.93    14.60
```

☺ significantly larger efficiency and very good `Err/Exp`
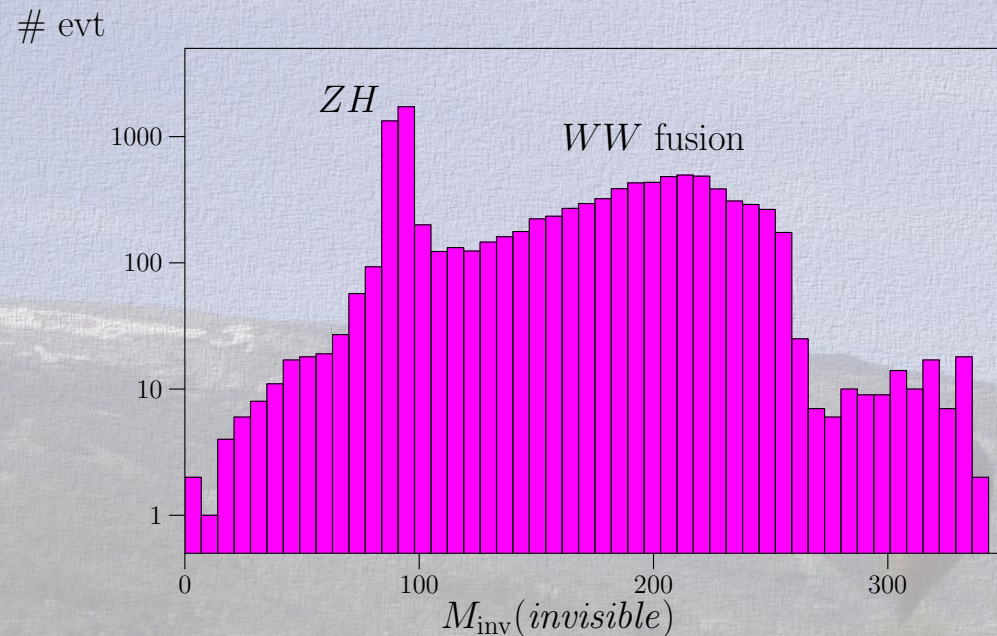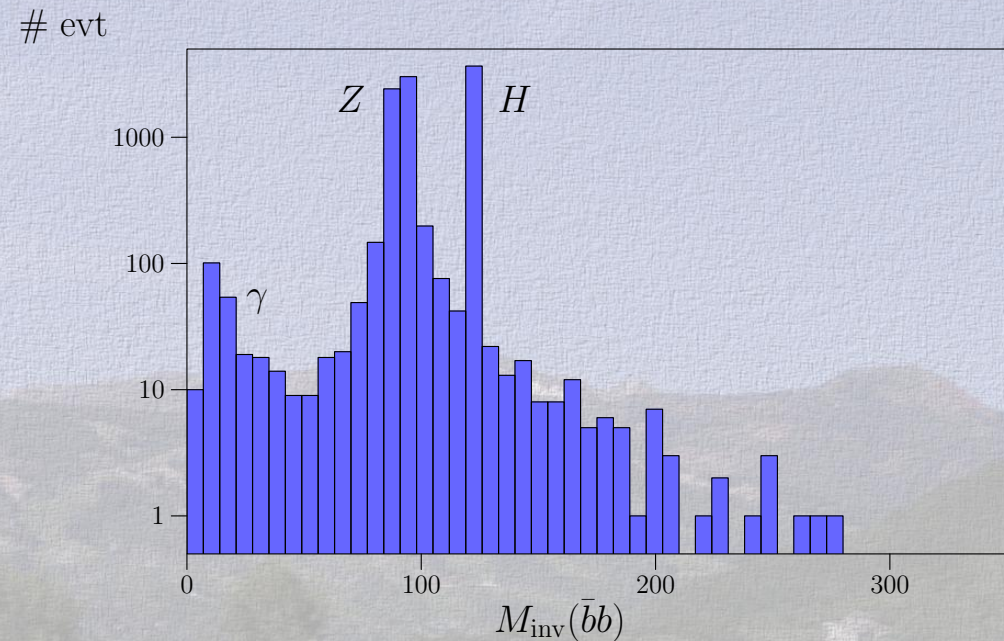
- Finally generate some events

```
! Integrating (fixed w.):  Generating 2 samples of 10000 events ...
   12      20000    5.8910540E+01   4.25E-01    0.72    1.02    11.64     0.05
```

☺ 15 min for adaptation, 10 min for 10,000 unweighted events on a Pentium II 233 MHz.

missing mass

invariant $b\bar{b}$-mass

$M_{\mathrm{inv}}(invisible)$

$M_{\mathrm{inv}}(\bar{b}b)$

Observations:

- adaption typically takes a bit longer than event generation

- adapted grids and weights can be saved and reloaded if the cuts and parameters are changed only slightly

WHIZARD is available from

`http://www-ttp.physik.uni-karlsruhe.de/Progdata/whizard/.`

Strongly interacting final states

- in principle, unweighted event generation already allowed feeding the events to a separate hadronization Monte Carlo (approach used for the TESLA TDR)

☹ but only for simple color configurations

☺ recently, Wolfgang Kilian has integrated an interface to PYTHIA with WHIZARD

☺ fully hadronized events are now just one WHIZARD flag (`fragmentation_method`) away

$= 1$ `CALL PYEXEC` (caveat: guesses color flow from ordering of external particles)

$= 2$ embed WHIZARD as external process(es) in PYTHIA (requires correct color amplitudes, availabe from MADGRAPH today, from O'Mega soon, hopefully . . .)

- make O'Mega more complete (complete QCD, MSSM & LED)

- add better interaction of O'Mega and WHIZARD to avoid redundancies

  – O'Mega purely symbolical: values of masses, couplings, energies and cuts still unspecified

  ∴ channel selection has to be done in WHIZARD

- efficient incoherent jet-like sums, avoiding combinatorial explosion

- loops (holy grail)

  – effective actions in O'Mega

  😟 straightforward, but tedious

  – numerical approach

  😟 hard problem, others have failed

  🙂 challenge!